Demonstration of Single-Event Effects Induced by Through-Wafer Two-Photon Absorption

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***Abstract*—The first demonstration of through-wafer two-photon absorption (TPA) single-event effects (SEEs) testing is presented. We interrogate the single-event transient (SET) response of several different nodes of the LM124 operational amplifier via TPA carrier injection through both the front and back (substrate) chip surfaces. The results reveal that the SETs and sensitivities produced in several different nodes by front-side and back-side irradiation are effectively identical, confirming the validity of this approach for SEE studies.**

***Index Terms*—LM124 operational amplifier, multiphoton absorption, nonlinear absorption, nonlinear-optical carrier injection, single-event effects (SEE), single-event transients (SET).**

I. Introduction

RECENTLY, a new method of laser-induced carrier injection for single-event effect (SEE) applications based on two-photon absorption (TPA) of high peak power femtosecond pulses at sub-bandgap optical wavelengths has been introduced and demonstrated [1], [2]. For excitation by TPA, the laser wavelength is chosen to be less than the bandgap of the semiconductor material, such that no carriers are generated (no optical absorption) at low light intensities. At sufficiently high intensities, however, the material can absorb two photons *simultaneously* to generate a single electron-hole pair [1], [3]–[5]. Because carrier generation in the two-photon process is proportional to the square of the laser pulse intensity, significant carrier generation occurs *only* in the high-intensity focal region of a focused laser beam [1], [4], [5]. This enables charge injection at any depth in the structure. Recently, the TPA technique was utilized in the front surface geometry to interrogate the complicated depth and position dependence of the single-event transient (SET) response of the LM124 quad operational amplifier [2].

A primary motivation for the development of the TPA SEE technique, however, is its ability to interrogate SEE phenomena through the wafer using back-side irradiation. This eliminates interference from the metallization layers, and circumvents many of the beam access issues associated with flip-chip-mounted parts. Recent related work has demonstrated a complementary method of back-side laser irradiation based on single-photon absorption that utilizes deeply penetrating optical pulses with the wavelength tuned near the bandgap of the substrate material [6], [7].

In this paper we present the first demonstration of the through-wafer TPA technique. We interrogate the SET response of several different nodes of the LM124 operational amplifier using both the top-side and back-side TPA techniques. It is found that the TPA-induced SETs generated with the two techniques are virtually identical, providing the first experimental demonstration of the validity of this approach.

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II. Two-Photon Induced SEE

Details of the two-photon-induced SEE technique are described elsewhere [1]. Briefly, the primary expression responsible for carrier generation in a semiconductor material is

$$\frac{dN(r,z)}{dt} = \frac{\alpha I(r,z)}{\hbar\omega} + \frac{\beta_2 I^2(r,z)}{2\hbar\omega} \tag{1}$$

in which I is the pulse irradiance, N is the density of free carriers, α is the linear (Beer's law) absorption coefficient, β_2 is the TPA coefficient that is proportional to the imaginary part of $\chi^{(3)}$ (the third-order nonlinear optical susceptibility), z is the depth in the material, and $\hbar\omega$ is the photon energy. In (1) the first term describes linear (Beer's law) absorption by a pulse propagating in the material; the second describes TPA, where the factor of two in the denominator accounts for the generation of *one electron-hole* pair for every *two absorbed photons*. The complete description of carrier generation and pulse propagation in a semiconductor material is a complex function of pulse intensity and phase, and requires the solution of a set of coupled differential equations, and is discussed elsewhere [1], [8].

The diagnostic characteristic of carrier injection by above-bandgap, single-photon absorption is the exponential decrease of injected carrier density as a function of depth in the material [1], [9]. While this characteristic leads to well defined and reproducible conditions for charge injection in the material, it precludes the possibility of carrier injection at a controlled depth. Conversely, when TPA is the primary means of carrier generation, the optical loss and penetration depth can be deterministically manipulated: because carrier generation is proportional to the square of the laser pulse intensity, *the generated carriers are highly concentrated in the high-irradiance region near the focus of the beam.* For a material that is transparent to the incident radiation, the high irradiance region can

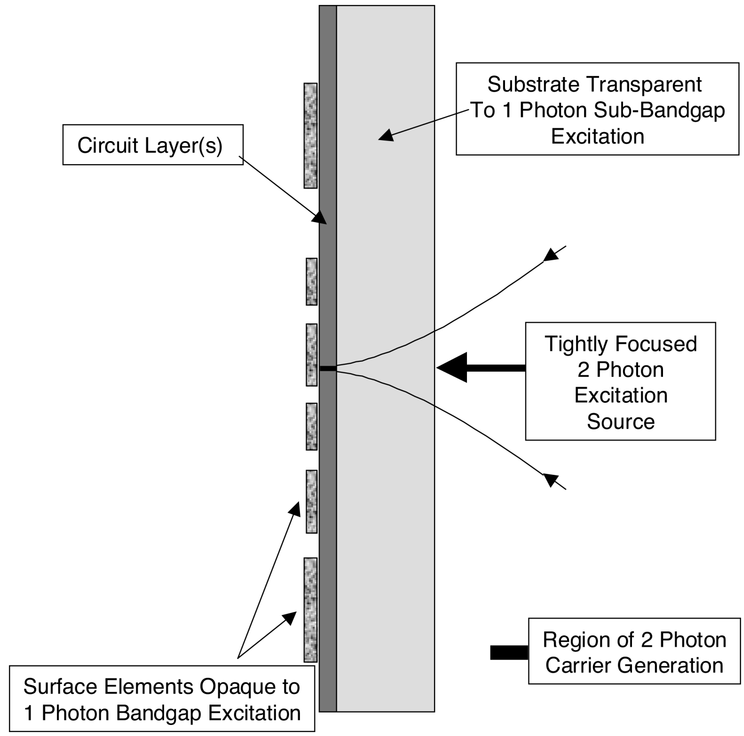

Fig. 1. Schematic diagram illustrating the through-wafer TPA approach to inducing SEEs in microelectronic devices.

be directed to any depth in the material by translation of the device under test (DUT) with respect to the laser focusing element. High purity silicon in the sub-bandgap region of the spectrum ($\lambda > 1.15$ μm) exhibits a negligible linear absorption coefficient, making carrier injection at controlled depths and through the back device surface possible, as is illustrated schematically in Fig. 1.

III. Experimental

The TPA SEE experimental setup has been described previously [1], [2]. The SET experiments at wavelengths below the silicon bandgap were performed using an amplified titanium sapphire laser system (Clark-MXR CPA 1000) that pumps a tunable optical parametric amplifier and produces 140 fs optical pulses at 1.26 μm with about 100 μJ of energy per pulse. The strong infrared (IR) beam is attenuated by a waveplate–polarizer combination to precisely control the pulse energy incident on the DUT, which is monitored with a calibrated large area InGaAs photodiode.

The DUT is mounted on a motorized xyz translation platform with 0.1 μm resolution, and the optical pulses are focused onto the DUT with a $100\times$ microscope objective resulting in a near-Gaussian beam with a diameter of 1.6 μm at focus [1]. All experiments are performed at room temperature (295 K). The DUT is imaged with a silicon charge-coupled device (CCD) camera and monitor. Since the 1.26 μm light is not detected by the silicon CCD array, a weak beam at the second harmonic (630 nm) of the sub-bandgap excitation wavelength is propagated (nearly) collinearly and used as a guide to image the specific device location irradiated with the sub-bandgap IR beam. For the top-side SET measurements, the visible beam is removed using a Schott RG715 long-pass filter.

The LM124 chips were obtained from National Semiconductor, Portland, ME, with the back side polished at NAVSEA Crane, Crane, IN. The unthinned chips (0.3 mm thick) were mounted (at NASA Goddard) in a metal can with a via drilled in the bottom to allow the laser light to pass through and enter the back side of the wafer. A special socket was designed so that front-side and back-side experiments could be performed on the same packaged device. For all experiments, the LM124 was operated in a voltage follower configuration with a short length of coaxial cable (6 in) and an 11 pF field-effect transistor (FET) probe connected to the output ($V_{dd} = 15$ V, $V_{ss} = -15$ V, and $\Delta V^{\rm in} = 5$ V). All experiments were performed with ac coupling.

Back-side experiments for some tested devices were marred by optical shadowing effects in which a portion of the optical beam was blocked by the front edge of the cylindrical via in the metal can. This was mainly a consequence of the 0.5 mm via length (due to the thickness of the base of the can) exceeding the Rayleigh range of the focused IR beam and acting as a limiting aperture. The fact that many of the transistors of interest were located near the edge of the via resulted in high diffractive energy losses to the IR beam which could be attributed incorrectly to propagation losses in the substrate. To eliminate the shadowing effect, the hole through the base of the can was beveled, and the chip was mounted to the can on three sides only, with the fourth side suspended over the open aperture. This procedure resulted in clear path for the beam to the DUT, and eliminated all shadowing effects.

IV. Results and Discussion

TPA SET measurements were performed on several nodes of two separate LM124 operational amplifier devices (devices 1

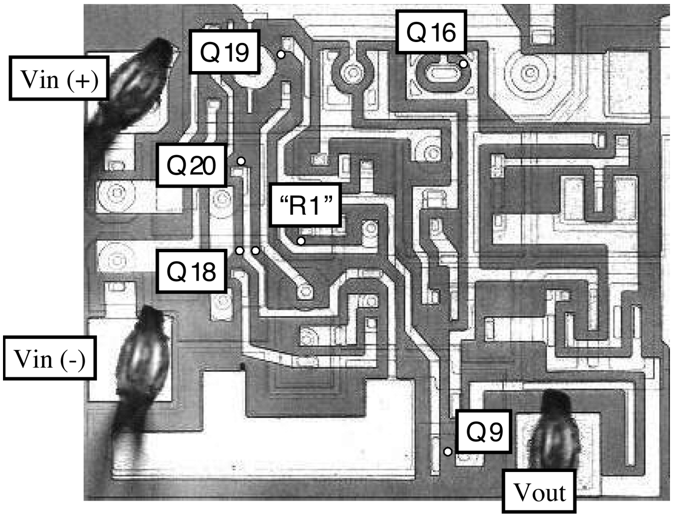

Fig. 2. Top-side photomicrograph of the LM124 operational amplifier illustrating the transistors relevant to this study and the locations (white dots) of the top-side two-photon-induced SET measurements.

and 2) using both front-side and back-side through-wafer irradiation. The locations interrogated using front-side irradiation are illustrated in Fig. 2, and the results are consistent with earlier measurements made using both single-photon (590 nm) and front-side two-photon excitation [1], [2]. For the back-side experiments, we presently do not have the capability for imaging the chip through the wafer. The different circuit nodes were identified using the known circuit layout (cf., Fig. 2) and their location relative to a specific registration locus on the chip. Transistor Q18 has a unique SET response that is not observed elsewhere on the device, so this transistor was used as the registration locus.

The experimental procedure is as follows. The front-side measurements were performed for the nodes of interest using the same laser pulse energy for each. The x–y position and depth (z) were optimized at each location to produce the largest transient. The device was then flipped over, and the unique SET signature for Q18 was located. With the incident laser pulse energy the same as for the top-side experiment, the x, y, and z adjustments were optimized to match the shape and amplitude of the Q18 transient produced by front-side irradiation. The other nodes of interest were then located by their position relative to Q18, and the resulting transients were recorded as for Q18. For example, Q20 is located directly above Q18 (100 μm in the "y" direction) in Fig. 2, and is easily located relative to Q18.

TPA-induced SETs measured for two locations of transistor Q18 of device 1 are shown in Fig. 3 for a laser pulse energy of 0.56 nJ incident on the surface of the device (the same energy was used for both the top-side and back-side measurements). For the Q18 data of Fig. 3, the x–y location was chosen to produce the unique triangular waveform shown. This location is away from collector C1 of Q18, toward the p^+ isolation that separates Q18 from Q20, as is indicated in Fig. 2 (cf., [2]). As is evident, the transients measured using the front-side and back-side techniques for these two nodes are nearly identical. The minor discrepancies evident in the data of Fig. 3 are considered insignificant, and are attributed to the experimental uncertainty associated with locating the precise xyz position to match the transient amplitude when performing the back-side measurement.

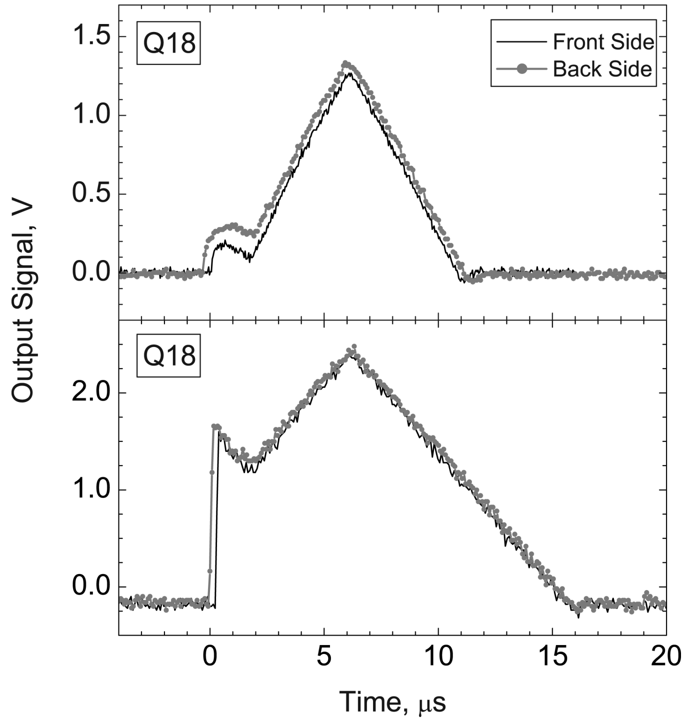

Fig. 3. Front-side and back-side (through-wafer) TPA SET measurements of device 1 for two different locations of transistor Q18 of the LM124 operational amplifier for a 0.56 nJ laser pulse energy at 1.26 μm.

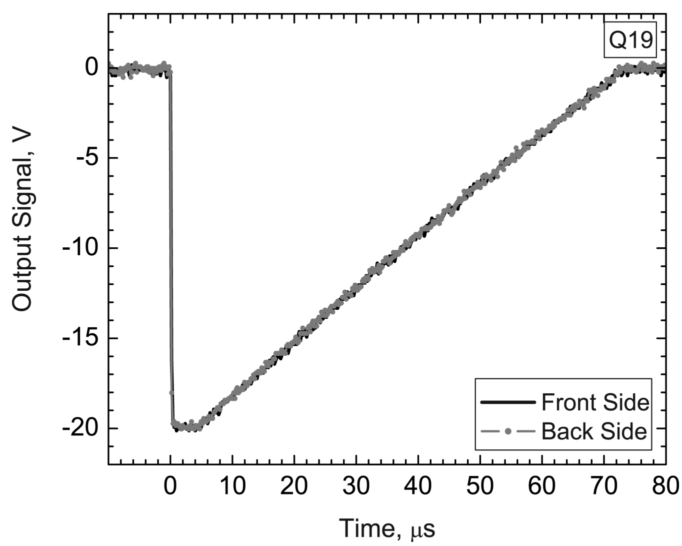

Fig. 4. Front-side and back-side (through-wafer) TPA SET measurements of device 1 for transistor Q19 of the LM124 operational amplifier for a 0.56 nJ laser pulse energy at 1.26 μm.

Fig. 4 shows the analogous front-side and back-side measurements for transistor Q19. The measurement procedure is similar to that for Q18 described previously, with the pulse energy the same (0.56 nJ) for the two measurements. In this case, once Q19 and its characteristic SET signature were located, and fine adjustments of the x–y position were made to optimize the signal amplitude. A final adjustment of the "z" position gives the result of Fig. 4. Again, the top-side and back-side

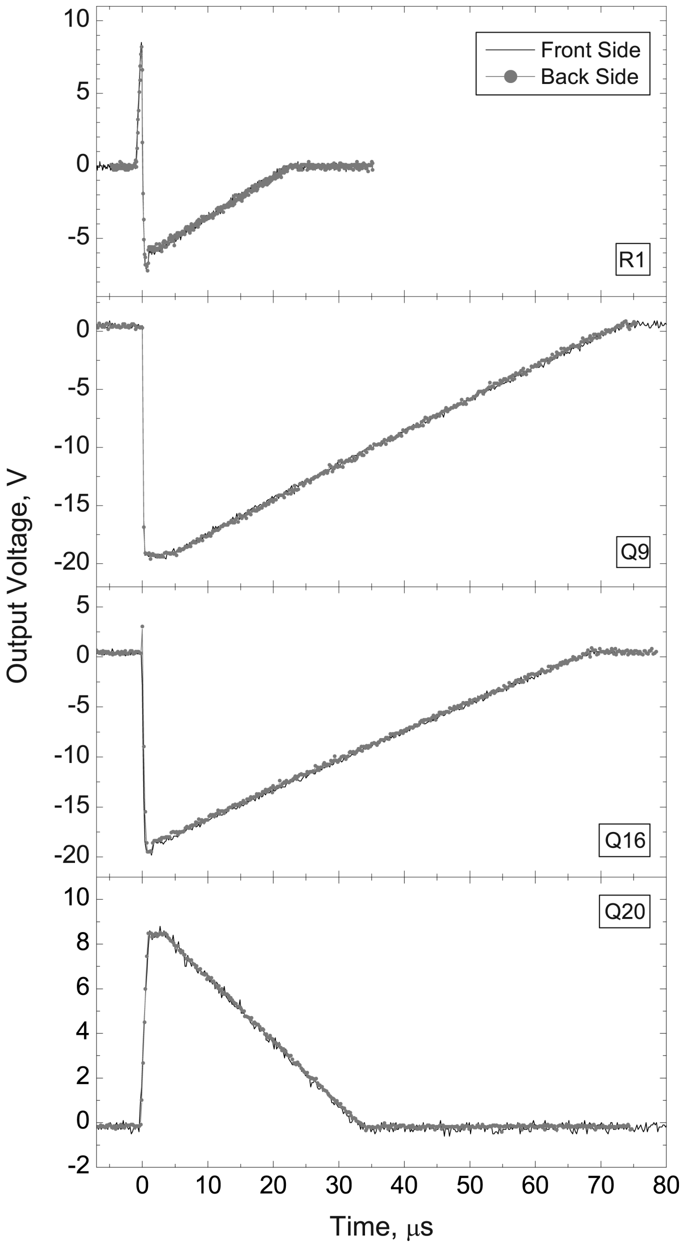

Fig. 5. Front-side and back-side (through wafer) TPA SET measurements for device 2 for "resistor" R1 and transistors Q9, Q16, and Q20 of the LM124 operational amplifier for a laser pulse energy at 1.26 mm. The pulse energy for the front-side and back-side measurements was different for each of the nodes.

transients are effectively identical. The results of Figs. 3 and 4 demonstrate clearly the viability of the back-side through-wafer TPA approach for SEE investigations. Further, these results reveal that, using the back-side TPA approach, it is possible to inject charge in a controlled manner that reproduces faithfully the charge deposition from front-side irradiation. And finally, consistent with the absorption spectrum of high-purity silicon [1], the results illustrate that, pulse propagation at 1.26 μm shows no detectable degradation by transmission through the unthinned (0.3 mm) silicon wafer.

As mentioned previously, because of the rapid divergence (short Rayleigh range) of the tightly focused laser beam, optical shadowing can be an issue for through-wafer measurements. Fig. 5 shows results for our initial mounting of device 2, where optical shadowing was an issue due to the cylindrical geometry of the access via. Top-side and back-side results for the floating base transistor (labeled as "resistor" R1 in the circuit diagram), and transistors Q9, Q16, and Q20 are shown in Fig. 5 for the laser spot locations indicated in Fig. 2. Because of the "shadowing" effect described above, to reproduce the shape and amplitude of the top-side transients as shown in Fig. 5 it was necessary to increase the laser pulse energy for the back-side experiment. The magnitude of this increase varied with the particular transistors (and their location on the chip). For each of the examples shown in Fig. 5 it was possible to reproduce both the SET pulse shape and amplitude simply by adjusting the laser pulse energy and, in agreement with the results of Figs. 3 and 4, the front-side and back-side transients are very nearly indistinguishable. For other nodes, such as some locations within Q18 and Q20 (which are located near the edge of the chip), it was not possible to reproduce both the amplitude and shape of the SET by varying the laser pulse energy.

Contrasting the results of Fig. 5 to those of Figs. 3 and 4 demonstrates that the differences in SET sensitivity can be traced to the via geometry and should not be attributed to the optical path through the substrate. These results furthermore indicate the importance of geometrical aspects of beam access to circuit nodes in quantitative laser SEE tests *in general*: optical path obstructions can limit access to circuit nodes whether the irradiation is in the front-side or back-side geometry. When the electrical and optical properties of the substrate material are known, the back-side technique may be the only means for quantitative testing due to dense metallization and other structures on the front surfaces of ICs.

We note that, for Q20, the top-side transient of Fig. 5 was obtained with the laser focus adjusted below the surface of the device, consistent with the results of [2]. In addition, it was verified that the complex depth dependence of Q20 reported previously [2] is reproduced with back-side excitation.

V. Conclusion

The TPA method represents a novel approach to SEE evaluation with unique capabilities not exhibited by other techniques. Previous work has revealed the strength of this technique for investigating the SET response of linear bipolar technologies [2]. The present paper demonstrates the utility of the nonlinear-optical TPA approach as a method for injecting carriers into the active regions of devices using through-wafer back-side irradiation. The back-side geometry eliminates interference from the metallization layers, and circumvents many of the issues associated with testing flip-chip-mounted parts. The results presented here represent the first experimental demonstration of the through-wafer TPA-induced SEE technique. Experiments performed on the LM124 operational amplifier (without wafer thinning) reveal that the SETs and sensitivities produced in several different nodes by front-side and back-side irradiation are effectively identical, confirming the validity of this approach.

Recent generation technologies are becoming increasingly complex, with multiple metallization layers becoming a major impediment to conventional top-side laser SEE testing. Additionally, the advent of flip-chip mounted devices renders both top-side laser testing and conventional heavy-ion testing impractical (or impossible). The present results reveal that the back-side TPA technique represents a potentially valuable alternative to the conventional techniques that can be made even more powerful by additional effort in the development of dedicated lasers and optical testing schemes.

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